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UTILITY PATENT APPLICATION TRANSMITTAL

(Only for new nonprovisional applications under 37 C.F.R. § 1.53(b))

Attorney Docket No.	07007-04
First Inventor or Application Identifier	Brassil, J.T.
Title	DYNAMIC BANDWIDTH ALLOCTION IN A RESERVATION SYSTEM
Express Mail Label No.	EH493500033 US

09/351597 07/12/99

APPLICATION ELEMENTS

See MPEP chapter 600 concerning utility patent application contents.

ADDRESS TO: Assistant Commissioner for Patents, Box Patent Application, Washington, DC 20231

1. [X] * Fee Transmittal Form *(e.g., PTO/SB/17)* *(Submit an original and a duplicate for fee processing)*
2. [X] Specification [Total Pages 12] *(preferred arrangement set forth below)*
   - Descriptive title of the Invention
   - Cross References to Related Applications
   - Statement Regarding Fed sponsored R & D
   - Reference to Microfiche Appendix
   - Background of the Invention
   - Brief Summary of the Invention
   - Brief Description of the Drawings *(if filed)*
   - Detailed Description
   - Claim(s)
   - Abstract of the Disclosure
3. [X] Drawing(s) *(35 U.S.C. 113)* [Total Sheets 4]
4. Oath or Declaration [Total Pages 4]
   - a. [X] Newly executed (original or copy)
   - b. [ ] Copy from a prior application (37 C.F.R. § 1.63(d)) *(for continuation/divisional with Box 16 completed)*
     - i. [ ] DELETION OF INVENTOR(S) Signed statement attached deleting inventor(s) named in the prior application, see 37 C.F.R. §§ 1.63(d)(2) and 1.33(b).

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5. [ ] Microfiche Computer Program *(Appendix)*
6. Nucleotide and/or Amino Acid Sequence Submission *(if applicable, all necessary)*
   - a. [ ] Computer Readable Copy
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ACCOMPANYING APPLICATION PARTS

7. [X] Assignment Papers (cover sheet & document(s))
8. [ ] 37 C.F.R.§3.73(b) Statement *(when there is an assignee)* [X] Power of Attorney
9. [ ] English Translation Document *(if applicable)*
10. [X] Information Disclosure Statement (IDS)/PTO-1449 [X] Copies of IDS Citations
11. [ ] Preliminary Amendment
12. [X] Return Receipt Postcard (MPEP 503) *(Should be specifically itemized)*
13. [ ] * Small Entity Statement(s) *(PTO/SB/09-12)* [ ] Statement filed in prior application, Status still proper and desired
14. [ ] Certified Copy of Priority Document(s) *(if foreign priority is claimed)*
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[ ] *Customer Number or Bar Code Label* *(Insert Customer No. or Attach bar code label here)* or [X] *Correspondence address below*

Name	MEIR Y. BLONDER				
	PRYOR CASHMAN SHERMAN & FLYNN LLP				
Address	410 PARK AVENUE - 9th FLOOR				
City	NEW YORK	*State*	NY	*Zip Code*	10022-4441
Country	USA	*Telephone*	212-326-0478	*Fax*	212-326-0806

Name (Print/Type)	MEIR Y. BLONDER	*Registration No. (Attorney/Agent)*	40,517
Signature	Meir Blonder	*Date*	July 12, 1999

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Application

for

United States Letters Patent

To all whom it may concern:

Be it known that

JOHN THOMAS BRASSIL

has invented certain new and useful improvements in

DYNAMIC BANDWIDTH ALLOCATION IN A RESERVATION SYSTEM

of which the following is a full, clear and exact description.

DYNAMIC BANDWIDTH ALLOCATION IN A RESERVATION SYSTEM

FIELD OF THE INVENTION

The present invention relates to dynamic bandwidth allocation in a reservation system.

BACKGROUND OF THE INVENTION

Reservation system networks are well known in the art and have been studied in relation to various distribution systems, such as satellites and cable, for carrying various media, such as data, voice or video.

In its simplest form, a distribution network using a reservation system includes upstream, user to headend, and downstream, headend to user, channels. The headend broadcasts on the downstream channel the various time slots per time frame during which each respective user may communicate back to the headend. During its allocated time slot a particular user requiring a certain amount of bandwidth will send a request upstream for a reservation for an amount of bandwidth. The headend then responds to that user indicating that the requested bandwidth, or some fraction thereof has been reserved and may identify the time slot(s) corresponding to that bandwidth. A tree topology of such a prior art network, is shown in Figure 1. As shown, N users are shown at 10 connected through a medium over which frames 30 of T time slots are transmitted to a headend 20.

As described above, available bandwidth over the network is dynamically allocated. The amount of bandwidth available to a user will vary depending in part on the user's requirements. Many existing systems, however, including some reservation systems, are static in that a pre-determined amount of bandwidth is allocated and always available to each user on the distribution

network. While this system is fair as between users, it may be a poor performer in terms of network efficiency. Often times it may occur that one user with a high demand will not have sufficient bandwidth, notwithstanding that the system as a whole is underutilized because another user is not at that time using all of the bandwidth reserved for its use. In addition, a static system is difficult to reconfigure when adding or removing users from the network.

Dynamic allocation of bandwidth can be more efficient than static allocation by accounting for the different needs of each user, at particular times. However, the system is not necessarily fair from a user point of view since heavy users can receive more bandwidth than relatively light users. While dynamic allocation schemes can be designed with greater degrees of complexity to achieve a fairer allocation, complexity introduces network latency, a concern described in more detail below.

A bandwidth allocation system simply takes user requests and assigns some feasible allocation of bandwidth. Dynamic (or adaptive) allocation algorithms vary the bandwidth allocated to each user based on online traffic measurement. Varying user allocations can extend the region of stability of user queues. A DBA system can be designed so that any user is capable of capturing the entire shared link bandwidth, if desired. Under bursty traffic, the utilization of the shared upstream link can be higher, and users can see lower latency than for a static allocation. However, DBA algorithms must be carefully designed to avoid both short and long term unfair bandwidth sharing among users, relative implementation complexity, and slow responsiveness to sudden arrival bursts.

It should be noted that the implementation complexity of different bandwidth allocation algorithms can vary greatly. Complexity is shared by both users and the headend's bandwidth allocator. Indeed, the implementation of each algorithm requires partitioning functionality between the headend and the user node, as well as tradeoffs between this functionality and the encoding of the

bandwidth requests and grants. One complexity measure useful in comparing different algorithms is the amount of information in an allocation request, and its encoding.

One typical type of dynamic allocation algorithm is referred to as state-based proportional, as the allocation is based on the user's state information. An example of useful user state is the current length of a user's queue. It is proportional in the sense that if there is insufficient bandwidth to satisfy all requests, a node will receive an allocation proportional to its request. Otherwise it will be allocated enough bandwidth to satisfy its request. This request embodies the composite "state" of user i at time t, and is typically chosen to be a function of user node parameters such as queue size and recent arrivals. Examples of request parameters include:

(i) Queue: A node requests enough slots to empty its queue in the current frame;

(ii) Prev: A node requests slots equaling a constant $c > 1$ times the number of arrivals in the current frame;

(iii) Queue+Prev: A node requests slots equaling the sum of its queue plus the number of arrivals in the current frame. For a single frame reservation latency, this request forms an estimate of the allocation needed to empty the queue at the end of the next frame $t+1$; and

(iv) Indicator: Each node signals an indication of the need for bandwidth in the current frame.

Depending on the type of distribution and the media being carried, dynamic or static allocation may be more appropriate. For example, static allocation may be more appropriate for voice communications since demand is fairly steady and its high quality requirement means bandwidth must be available. On the other hand, for media such as Internet traffic which is very bursty, a dynamic allocation may be more appropriate. Indeed, with Internet traffic, the network may experience fluctuations from high demand to no demand can occur from time frame to time

frame.

Recently, a new network distribution medium is being promoted to bring a variety of media, including Internet access, directly to the house. This network is referred to as Fiber to the Home ("FTTH"). In accordance with the industry protocol Full Service Access Network ("FSAN"), being promoted for FTTH, a reservation system is employed over an optical network. Since FTTH is designed to include Internet traffic, it is important to design an effective method of dynamic allocation of bandwidth to handle the bursty traffic.

One common network design for FTTH is a passive shared-media optical distribution network. In this distribution system the upstream and downstream channels are logically separated with coarse-grain wavelength division multiplexing. The downstream broadcast channel uses optical power-splitting to permit communication from headend to all users. The upstream channel optically combines user transmissions. A fixed time-slot time division multiplexed algorithm ("TDMA") reservation protocol permits conflict-free access to the shared upstream link. The necessary slot time synchronization between users is achieved by extracting timing information from the shared downstream channel, coupled with an initial delay compensation procedure to logically set users at an equal distance from the optical signal combination point.

Time slots on the upstream link are organized into fixed length logical frames. In each upstream frame t each user transmits to the headend a request for time slots in a future frame. Typically, a slot (or minislot) is reserved for each user to issue an upstream bandwidth reservation request. After receiving and processing the N requests (the sum of all user's requests) transmitted upstream during frame t, the headend broadcasts downstream the slot reservations for each user in a future upstream frame $t + \delta$, $\delta = 1,2$, etc. Hence, the parameter δ indicates the reservation latency in

frames.

Reservation protocols of this type have been well studied in various settings including satellite systems and more recently in broadband residential access networks. One such protocol is Conflict-Free Multiple Access ("CFMA"), proposed for satellite-based systems. In CFMA each user node indicates a bid for bandwidth in a future frame by setting a bit in a dedicated TDM reservation minislot at the start of each frame. All frames are broadcast to all user nodes. Each user has a predetermined priority for capturing each time slot in a frame; an active bidder acquires all time slots for which it has highest priority among the other active bidders. *See* H.R. Hwa, "*A Framed Aloha System*," in Proc. PACNET Symposium (August 1975), hereby incorporated by reference as if fully set forth herein.

Thereafter, a centralized system was proposed where ground stations communicate queue length to an intelligent headend at the start of a frame; the headend allocates bandwidth and specific slots and broadcasts a future frame slot allocation (i.e. a 'grant') downstream. *See* S. Ng and J.W. Mark, "*A New Multi-Access Model for Packet Switching with an Intelligent Satellite*," in Proc. International Computer Communications Conference, (August 1976), hereby incorporated by reference as if fully set forth herein.

Returning to the issue of bandwidth allocation, latency, or delay in responding to a request can have an adverse impact on how efficient bandwidth is allocated, for the following reason. Consider a system where requests are based on queue length, as is traditionally the circumstance, with a delay of five frames. Typically, these systems are simply designed with no memory of prior requests. At frame t the user will simply transmit to the headend its queue length, which may be ten time slots. At time $t+1$ the user has not yet received a response, yet its queue length is still ten. In

fact, the queue length may have grown. In either case the user will again send a request for at least the same ten time slots. The same is true at times t +2, t +3 and t +4. Consequently, five requests for the same ten time slots are sent. However, as soon as the first response is received the user will empty its queue, notwithstanding that it will receive ten time slots in each of the subsequent four frames. Those slots are wasted. The user was over allocated.

It may be possible to address the above scenario by adding memory to the user such that it will recognize when bandwidth was already requested for its queue. However, this introduces a degree of complexity in the system which will aggravate the latency of the system.

A collection of dynamic bandwidth allocation algorithms were recently introduced to address the support of IP traffic over a connection-oriented network. However, the focus of that study was the performance of algorithms for a single user, given essentially an unlimited amount of bandwidth available for allocation and a single frame reservation latency. *See* Y. Afek et al., "*Dynamic Bandwidth Allocation Policies*," in 2 IEEE Infocom '96 pp. 8808-887 (March 1996), hereby incorporated by reference as if fully set forth herein. However, the collection of algorithms do not support multiple users competing for finite bandwidth, with arbitrary reservation latency.

At present, network designers and those who consider issues relating to bandwidth allocation on real network systems, either ignore the effect of latency or address it only over long periods of time. There is no known method of dynamic bandwidth allocation that addresses latency over a very short period of time, for example, time frame by time frame. The bursty nature of Internet communication, however, requires a frame-level bandwidth allocation policy. It would thus be desirable to have a dynamic bandwidth allocation method which achieves high utilization of the

shared upstream link, low headend processing complexity, fair bandwidth sharing between users, and low latency.

It should also be noted that with FSAN the issue of latency is aggravated by the fact that the speed of the upstream and downstream channels are mismatched. In other words, more than one request is sent upstream for every frame sent downstream.

SUMMARY OF THE INVENTION

Accordingly, it is desirable to have a method of dynamic bandwidth allocation, especially for use in connection with a FTTH distribution system, that addresses and reduces the effects of network latency. In accordance with the method of the present invention a state-based dynamic algorithm is scaled down by a factor equal to the reservation latency (measured in frames) in the system. Thus where queue length is the state parameter of the dynamic algorithm, the request is limited to the queue length divided by the reservation latency (frames).

Alternatively, where memory is available, the algorithm can be further modified in accordance with the present invention by requesting bandwidth based on both the demand in prior frames and the current demand.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts the topology of a prior art distribution network.

DETAILED DESCRIPTION OF THE INVENTION

Throughout the following discussion it is assumed that each user has an infinite queue

capacity, arrivals at each user's queue are of fixed size — an ATM cell — and exactly one cell can be transmitted in each time slot. Each upstream frame comprises T time slots for data traffic, and R reservation time slots, so the maximum utilization for best-effort data traffic is limited to $T/(T+R)$. It is also assumed that the system is homogeneous, such that the same bandwidth allocation algorithm operates at each node.

To facilitate the following discussion the following variables for each user i are defined:

λ_i^t: The number of arrivals (ATM cells) to user i in frame t.

Φ_i^t: The number of time slots requested by user i in frame t.

$\mu`_i^t$: The number of time slots allocated to user i in frame t.

μ_i^t: The number of departures from user i in frame t.

q_i^t: The number of cells queued by user i at the *end* of frame t.

It follows that the size of user i's queue after t is equal to $q_i^{t-1} + \lambda_i^t - \mu_i^t$. Note that in a given frame a user's slot allocation might exceed its number of queued cells, and consequently exceed its actual departures. It follows then that the utilization of the data slots for the system is defined as $1/t(\Sigma_t \Sigma_i \mu_i^t/T)$. This however, does not include the reservation slot overhead, which is omitted from this discussion.

In accordance with the present invention a network designer can choose to accept higher delay to improve efficiency by modifying algorithms to be less aggressive than prior art methods described above, when in the face of reservation delay, δ. Specifically, any state-based request by user i at time t should be modified to limit the total number of requested slots over a number of frames, to the reservation latency. Thus, a simple class of memoryless DBA algorithms can be

written by scaling any of the bandwidth requests discussed above, *i.e.* **queue,** by a factor equal to the reservation latency. Thus for example, the request at time *t* may be set at q_i^t/δ.

This less aggressive strategy maintains the overall efficiency near unity, the number of time slots used by all users at time *t* will be very close to the number of time slots allocated to all users at time *t*, with a relatively small increase in delay. It also has the potentially beneficial property of smoothing single frame arrival bursts over δ upstream frames.

In one advantageous embodiment of the present invention a slightly more aggressive request can be made where the system provides for a small amount of memory for each user, sufficient to store information about a user's state during the previous frame. In this system user *i* will request at time *t*, the greater value as between the number of arrivals at the user's queue λ_i^t, and q_i^t/δ. This approach improves upon the responsiveness of simply requesting q_i^t/δ, by immediately responding with a request equal to the number of cells in an arrival burst.

Referring to Figures 2-4 a very coarse illustration is shown of the difference in efficiency between the prior art method and the two embodiments of the present invention discussed above. In each of these charts a relationship is shown over 10 time instants, between the number of new arrivals to a user at that time instant, number of time slots available to that user at that time instant, the user's queue size at the end of that time instant and the number of requests sent to the headend by that user. For ease of illustration, it is assumed that each time instant corresponds to a frame period and that the reservation latency in the system is three time frames.

Referring to Figure 2, the data reflects a dynamic algorithm in which the user always requests its queue size. No new arrivals appear to the user during the ten time instants being observed.

However, the user begins with a queue size of 12. As is readily seen, with a reservation latency of three frames, the user makes three requests for 12 slots. However at t=3, 12 slots are delivered by the headends and the user's queue is empty. Nonetheless, the user continues to receive over the next two frames, a total of 24 unneeded slots.

In accordance with the present invention, Figure 3 records that the user requests only 1/3 of its queue size. Therefore it begins to receive 4 slots at t=3 and continues to receive slots through t=7. However, instead of 24 wasted slots, there are only five. Figure 4 demonstrates where a new arrival for three slots occurs at t=5. In accordance with the second embodiment of the invention, the user requests the greater of 3, or 1/3 of its queue size at the end of that time instant -- which for Figure 4 is 3/3 or 1. Thus the user requests 3 time slots. As shown in Figure 4, after all requests are satisfied, only five time slots were wasted.

The foregoing merely illustrates the principles of the present invention. Those skilled in the art will be able to devise various modifications, which although not explicitly described or shown herein, embody the principles of the invention and are thus within its spirit and scope.

WHAT IS CLAIMED IS:

1. An improved dynamic bandwidth allocation method in a reservation network comprising one or more users and at least one headend, wherein one or more of said users request respective allocations of bandwidth based on a state parameter of said requesting user, said headend dynamically allocating bandwidth to one or more of said users in response to said respective requests, said headend responding to each of said requesting users with said allocated bandwidth, said response being delayed for a period of time which is a function of a reservation latency δ of said reservation system, said improvement comprising the step of scaling said state-based request by a factor of $1/\delta$.

2. The method of claim 1 wherein said state based request equals the size of a queue q_i of a user *i* and wherein said request for bandwidth by user *i* at time *t* equals q_i^t/δ.

3. The method of claim 1 wherein said reservation network includes memory available to a user *i* sufficient to store historical information about said state parameter of user *i*, the improvement further comprising the step of each user requesting at a time instant *t* an amount of bandwidth equal to the greater value as between the number of arrivals of cells at said user's queue, q_i, at said time instant *t*, (λ_i^t) and q_i^t/δ.

ABSTRACT

In a reservation network designed to carry bursty traffic an improved dynamic bandwidth allocation method accounts for reservation latency. In one advantageous embodiment wherein the system is memoryless, a user will request its queue size divided by the reservation latency in the system. Alternatively, a small memory based system can achieve further efficiencies by making available to a user a frame length amount of memory. The user can then request the greater as between its queue size divided by the reservation latency and the number of current arrivals at the user.

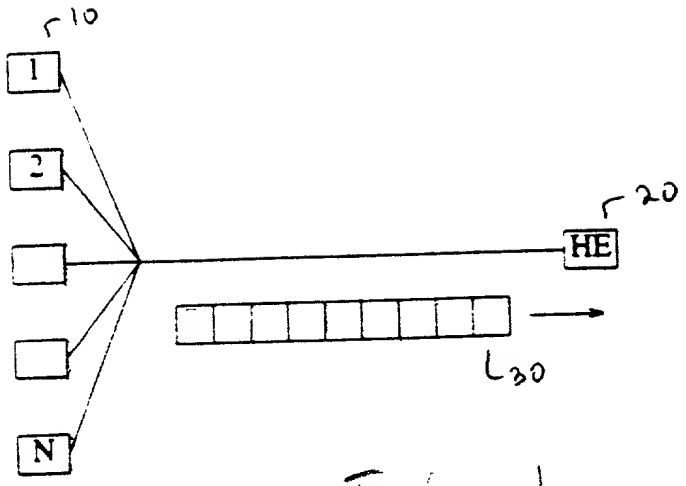

FIG. 1

Time Instant	# of Arrivals	# of Slots from Headend	Queue Size	# of Slots Requested
t=0	0	0	12	12
1	0	0	12	12
2	0	0	12	12
3	0	12	0	0
4	0	12	0	0
5	0	12	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0

Number of Wasted Slots 24

Figure 2

Time Instant	# of Arrivals	# of Slots from Headend	Queue Size	# of Slots Requested
t=0	0	0	12	4
1	0	0	12	4
2	0	0	12	4
3	0	4	8	3
4	0	4	4	2
5	0	4	0	0
6	0	3	0	0
7	0	2	0	0
8	0	0	0	0
9	0	0	0	0

Number of Wasted Slots 5

Figure 3

Time Instant	# of Arrivals	# of Slots from Headend	Queue Size	# of Slots Requested
t=0	0	0	12	4
1	0	0	12	4
2	0	0	12	4
3	0	4	8	3
4	0	4	4	2
5	3	4	3	3
6	0	3	0	0
7	0	2	0	0
8	0	3	0	0
9	0	0	0	0

Number of Wasted Slots 5

Figure 4

IN THE UNITED STATES
PATENT AND TRADEMARK OFFICE

Declaration and Power of Attorney

As the below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor of the subject matter which is claimed and for which a patent is sought on the invention entitled **DYNAMIC BANDWIDTH ALLOCATION IN A RESERVATION SYSTEM** the specification of which is attached hereto.

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by an amendment, if any, specifically referred to in this oath or declaration.

I acknowledge the duty to disclose all information known to me which is material to patentability as defined in Title 37, Code of Federal Regulations, 1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

None

I hereby claim the benefit under Title 35, United States Code, 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, 112, I acknowledge the duty to disclose all information known to me to be material to patentability as defined in Title 37, Code of Federal Regulations, 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application:

None

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

I hereby appoint the following attorney(s) with full power of substitution and revocation, to prosecute said application, to make alterations and amendments therein, to receive the patent, and to transact all business in the Patent and Trademark Office connected therewith:

Lester H. Birnbaum	(Reg. No. 25830)
Richard J. Botos	(Reg. No. 32016)
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Craig J. Cox	(Reg. No. 39643)
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Martin I. Finston	(Reg. No. 31613)
James H. Fox	(Reg. No. 29379)
William S. Francos	(Reg. No. 38456)
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Patricia A. Verlangieri	(Reg. No. 42201)
John P. Veschi	(Reg. No. 39058)
David Volejnicek	(Reg. No. 29355)
Charles L. Warren	(Reg. No. 27407)
Jeffrey M. Weinick	(Reg. No. 36304)

Eli Weiss (Reg. No. 17765)

I hereby appoint the attorney(s) on ATTACHMENT A as associate attorney(s) in the aforementioned application, with full power solely to prosecute said application, to make alterations and amendments therein, to receive the patent, and to transact all business in the Patent and Trademark Office connected with the prosecution of said application. No other powers are granted to such associate attorney(s) and such associate attorney(s) are specifically denied any power of substitution or revocation.

Full name of sole inventor (or 1st joint inventor): John Thomas Brassil

Inventor's signature John Thomas Brassil Date 7/7/99

Residence: 137 Amanda Lane, Los Gatos, CA 95032

Citizenship: USA

Post Office Address: same as above

ATTACHMENT A

Attorney Name(s): Maxim H. Waldbaum Reg. No.: 26,244
Meir Y. Blonder 40,517

Telephone calls should be made to Meir Y. Blonder at:

Phone No.: 212-326-0478

Fax No.: 212-326-0806

All written communications are to be addressed to:

Meir Y. Blonder, Esq.
PRYOR CASHMAN SHERMAN & FLYNN LLP
410 Park Avenue
New York, NY 10022-4441